IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Application of:	Teruhiko HAGIWARA	Confirmation No.:	1331
Serial No.:	09/803,819	Art Unit:	2859
Filed:	March 13, 2001	Examiner:	Dixomara VARGAS
For:	NMR LOGGING USING TIME-DOMAIN AVERAGING	Attorney Docket No:	7420-081-999

DECLARATION OF THE INVENTOR UNDER 37 C.F.R. § 1.131

Assistant Commissioner for Patents
Washington, DC 20231

Sir:

I, Teruhiko HAGIWARA, do declare and state that:

1. I am a citizen of Japan residing at 9415 Basson Drive, Houston, Texas, 77025.

2. I am the sole named inventor of the invention disclosed and claimed in the above-identified patent application, Serial No. 09/803,819 filed on March 13, 2001.

3. I understand that U.S. Patent No. 6,452,389, having an effective date of February 7, 2001, has been cited against the claims of the present application in an Office Action dated September 20, 2005. I am providing this Declaration to "swear behind" the effective date of the '389 patent.

4. Attached hereto is Exhibit A, which is a copy of an invention disclosure submitted by me to Halliburton Energy Services. The disclosure describes NMR logging using time domain averaging.

5. I have reviewed the document in Exhibit A. I confirm that I conceived the invention disclosed in the document in Exhibit A before February 7, 2001 and diligently worked toward the filing of the present application on March 13, 2001. Although the dates have been redacted, I further confirm that the dates on the document are prior to February 7, 2001.

6. I declare further that all statements made in this Declaration of my knowledge are true and that all statements made on information and belief are believed to be true and further that these statements are made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issuing thereon.

Dated: Nov. 17, 2005

Teruhiko Hagiwara

Teruhiko HAGIWARA

Exhibit A: Invention Disclosure - Time-domain average method to increase S/N ration in single event echo-train in high-speed NMR Logging and to sharpen the spatial resolution of NMR logging.

HALLIBURTON ENERGY SERVICES GROUP

 INVENTION DISCLOSURE P.M. No. ______

TITLE: **Time-domain average method to increase S/N ratio in single event echo-train in high-speed NMR Logging and to sharpen the spatial resolution of NMR logging.**

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EMPLOYEE NO. ____________ ENTITY/DEPT.:__________

First M. Last

Address: Street City State Zip

Description of Invention: Give a brief description of the invention, and where possible a sketch. Do not write on back of this sheet. If additional space is necessary, use additional disclosure sheets (R&S 2311) and number consecutively. Sign and date each sheet and have each witnessed. Witnesses must be persons capable of understanding invention. If invented prior to date on this sheet, give full details-date, to whom disclosed, identify drawings, if any, etc. If used in the field, specify for what company and designate well and date.

This patent concerns a new processing method to increase signal-to-noise ratio (S/N) of NMR echo-train logging data when NMR logging was performed at high logging speed and conventional stacking technique over multiple echo events cannot be applied to increase the S/N ratio. The new method enables us to run NMR logging at higher speed and obtain T_2 inversion data without stacking echo train data from multiple events.

Background

One of the key information sought from the NMR logging data is the T_2 decay time distribution which may be closely related to the pore size distribution of the rock formation. From the T_2 decay time distribution, the capillary bound water volume may be estimated, for instance. The T_2 distribution is obtained by inversion of echo train data. Inversion of echo train is greatly affected by noise. In order to reduce the effect of noise and increase the signal-to-noise ratio, stacking of multiple echo train data is commonly exercised, by assuming that noise is of random nature. For instance, Fig.1 illustrates that the average echo train from 10 events is affected with much less noise than the echo train from single event.

In actual logging, the tool is moving at certain speed, and echo train from each event is not collected at the same logging location or depth. When the logging speed is slow, the tool moves only short distance. Hence, one may assume that the earth formation is of nearly constant property over the short distance, and stacking of multiple events from different depth may be acceptable.

However, the logging speed is fast, the tool moves longer distance and the formation property may change significantly over the distance. As a result, stacking of echo train data from multiple events reduces apparent spatial resolution of measurements beyond the intrinsic resolution of the tool.

Merit of Present Invention

As we describe below, the present invention uses time-domain average of single echo-train data to increase the S/N ratio, but not stacking of echo-train from multiple events, and hence, achieves higher spatial resolution. The S/N ratio can be increased also by application of both the time-domain-average and stacking together. In this case, one needs less number of stacking events and higher resolution will be resulted.

The concept of time-domain averaging is not new. For instance, the US Patent No. 5,219,137 (Freedman) and 5,381,092 (Freedman) also utilize the time-domain averaging in order to compress logging data at downhole (in a wellbore) prior to transfer the data to a surface apparatus. However, the present invention uses the time-domain averaging, not for data compression, but to increase S/N and to enhance vertical resolution of the log measurements. In the present invention, the time-domain averaging is applied to the log data after data transmission.

Present Invention

The T_2 decay time distribution is obtained by inverting the time-domain echo train data by assuming the physical model:

$$Echo(t) = \sum_{T_2} \phi(T_2)\exp(-t/T_2) + Noise$$

where $\varphi(T_2)$ is the porosity (or population) of the pores corresponding to the exponential decay time T_2.

For simplicity, we omit the effect of partial polarization due to the longitudinal relaxation time T_1. It can be included, if necessary. One such example of echo-train is plotted in Fig.1, where the echo train is generated from the T_2 distribution, $\varphi(T_2)$, of Fig.2. Because of noise, the inverted T_2 distribution obtained from this single event echo-train, which is also shown in Fig.2, is different from the model input.

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Signature of Inventor

Signed at ______________________ this [redacted]

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TITLE: **Time-domain average method to increase S/N ratio in single event echo-train in high-speed NMR Logging and to sharpen the spatial resolution of NMR logging.**

To reduce the effect of random noise, it is commonly practiced to stack echo-trains from multiple number of events. See Fig.3. Fig.4 shows such stacked (averaged) echo trains obtained from 10 events. Significant reduction of random noise is observed. The inverted T_2 distribution from the 10 event stacked echo train is closer to the model input, as illustrated in Fig.5.

Stacking of multiple event data causes worsening of spatial resolution of NMR logging, as the tool is moving in usual logging measurements. The tool moves considerable distance at a high logging speed. The formation property may change significantly over the distance. While single event echo train provides information of formation property for an interval determined by the intrinsic spatial resolution of the tool, the stacked echo train data provides formation property averaged over the distance to cover such multiple events. As a result, the spatial resolution of the measurement is greatly reduced beyond the intrinsic resolution of the tool.

The S/N ratio can be increased without stacking echo train data from multiple events and thus without worsening the spatial resolution at high logging speeds, but by taking time-domain-average. (In this method, the spatial resolution is not worsened at the price of the resolution in time domain.) See Fig.6. Namely, construct a time domain averaged echo train as follows: For time t, take an average of echo over the time interval of Δ, as defined by

$$Echo_\Delta(t) = \int_t^{t+\Delta} dt' Echo(t') / \Delta .$$

It is crucial that the noise in the averaged echo is still random. To ensure that, the averaged echo separated by time interval of Δ is considered. Namely, the averaged echo train at $t=t_0, t_0+\Delta, t_0+2\Delta, \ldots, t_0+N\Delta$ is used to obtain T_2 distribution. Fig.7 shows such a time-domain averaged echo train averaged over 10 sampling points. In this example, the single echo train has 300 data points at $t/T_E=1, \ldots, 300$ (with T_E=1.2 ms). As Δ=12 ms (10 sampling points), the averaged echo has 30 (=300/10) data points. The inverted T_2 distribution obtained from this time-domain-averaged echo is closer to the model input than the one from a single echo, as illustrated in Fig.8. Note that the following equation is used to estimate T_2 distribution:

$$Echo_\Delta(t) = \sum_{T_2} \phi(T_2) T_2 (1-\exp(-\Delta/T_2))\exp(-t/T_2) + Noise$$

$$= \sum_{T_2} \tilde{\phi}(T_2)\exp(-t/T_2) + Noise$$

where

$$\tilde{\phi}(T_2) = \phi(T_2) T_2 (1-\exp(-\Delta/T_2))/\Delta$$

Note that this T_2 distribution mapped from this new echo train data has the resolution of Δ, in contrast to the resolution of unit time interval from the original echo train data. This is because the time domain averaging is performed uniformly over the entire time domain using the constant time interval Δ. This requirement can be relaxed in a more general time domain averaging method below.

In order to obtain the T_2 distribution in full range, especially at shorter T_2, and to retain high T_2 resolution at shorter T_2, it is necessary to keep shorter averaging interval Δ at the earlier echo time though the averaging interval has to be larger at later echo time where S/N ratio decreases considerably. Hence, the above window averaging can be modified for variable time interval Δ_k at time t_k. Namely, we average the echo train at time t_k over the window interval of Δ_k as,

$$Echo_\Delta(t_k) = \int_{t_k}^{t_{k+1}-1=t_k+\Delta_k} dt' Echo(t') / \Delta_k$$

It is again crucial that the noise in the averaged echo is still random. To ensure that, the averaged echo train sampled at $t=t_0$, $t_1= t_0+\Delta_0+1$, $t_2= t_1+\Delta_1+1$, $t_{N-1}+\Delta_{N-1}+1$ should be used to obtain T_2 distribution. Namely, the averaging interval should not overlap. The interval width Δ_k can be unit interval, consisting of single echo time. Fig.9 illustrates such time-domain averaging intervals, where the first five echo data are raw data without averaging, and the following 15 echo windows are two time unit length for k=6-10, 4 unit length for k=11-15, 7 unit length for k=16-20, and the rest is averaged over constant 10 unit length. The T_2 distribution can be obtained from this time-domain-averaged echo by the following equation:

$$Echo_\Delta(t_k) = \sum_{T_2} \phi(T_2) T_2 (1-\exp(-\Delta_k/T_2))\exp(-t_k/T_2) + Noise$$

$$= \sum_{T_2} \tilde{\tilde{\phi}}(T_2;\Delta_k(t_k))\exp(-t_k/T_2) + Noise$$

where

$$\tilde{\tilde{\phi}}(T_2;\Delta_k(t_k)) = \phi(T_2) T_2 (1-\exp(-\Delta_k(t_k)/T_2))/\Delta_k(t_k)$$

Note that the window width Δ_k depends on the echo time t_k.

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Stacking of multiple event echo train data and time-domain averaging can be combined together. For instance, instead of taking 10- event stacking or time-domain averaging over 10 sampling points, one can take 5-event stacking and the apply time-domain averaging to increase the S/N ratio but not to worsen the vertical resolution much.

Figures

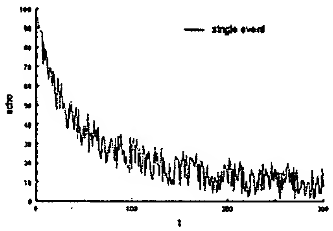

Fig1. Single event echo-train

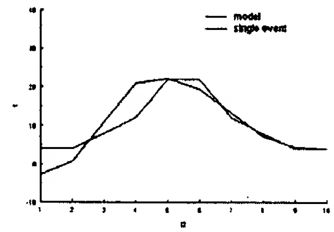

Fig.2 Inverted T_2 distribution from single echo-train data.

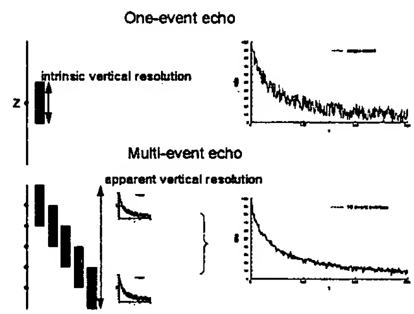

Fig.3 Multi-event echo stacking

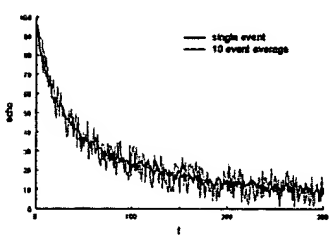

Fig.4 Stacked echo-train from 10 events

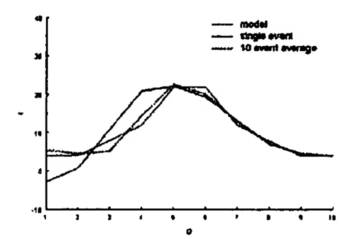

Fig.5 Inverted T_2 distribution from stacked echo-train data.

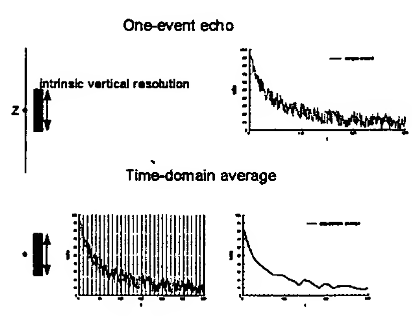

Fig.6 Time-domain average

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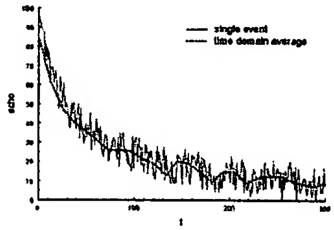


Fig.7 Time-domain averaged echo-train

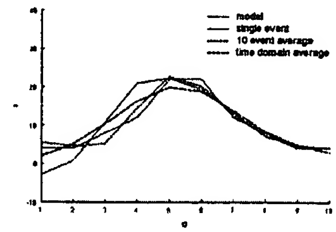
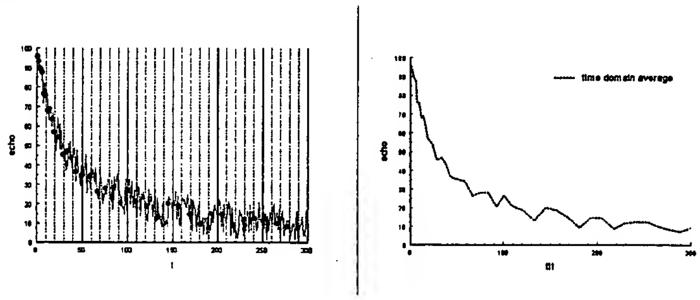


Fig.8 Inverted T_2 distribution from time-domain averaged echo-train

Fig.9 Time-domain averaged echo-train with variable window width



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